SOIL CLASSIFICATION OF HUMID WESTERN ETHIOPIA: A TRANSECT STUDY ALONG A TOPOSEQUENCE IN DIDESSA WATERSHED

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Abstract

Little has been studied on genesis and properties of soils in Western Ethiopia. This study was conducted to understand the pedogenesis, and to classify benchmark soils in Didessa watershed along a toposequence. The six soil profiles are representative of low, mid and highland positions within an elevation range from 1273 to 2700 meters above sea level along a 53-km long transect. Their pedological processes, soil properties and classification are discussed in context of soil forming factors and sustainable soil use. Melanization, cheluviation (chelation) of organo-mineral substances, oxidation of iron and leaching of iron compounds and basic cations, clay translocation, de-alkalization, and acidification were major pedological processes at the upland soils while erosion took place at shoulder positions. Calcification and pedoturbation (vertization) were major pedological processes in the lowland and melanization was also observed there. The surface horizons of these very deep soils had a loamy texture while the subsurface horizons were clayey. Leaching of basic cations increased with elevation. The U.S. Soil Taxonomy classification identified a soil sequence consisting of Typic Hapludults, Typic Ferrudalfs, Typic Rhodudalfs and Typic Hapluderts while the World Reference Base classified the corresponding soils as Ferric

Rhodic Alisols, Ferric Rhodic Luvisols, Ferric Chromic Luvisols, and Calcic Pellic Vertisols. Numerical hierarchical cluster analysis identified similar and dissimilar horizons in the soil catena. Ultisols were developed on tertiary basalt at midland, Alfisols were developed on tertiary basalts and granitic gneisses at midland and highland, and Vertisols were developed on alluvium and colluvium at lowland. The relief characteristics, lithologic units, agro-ecology and land use covered by the current study are typical of much of the Western and Southwestern Ethiopia. The study indicated that Didessa toposequence has three soil orders (reference groups) that need different management requirements for sustainable soil use. Thus, the transect serves as a model of soil development and soil management in humid Western Ethiopia.

Key words: Alfisols; Cluster Analysis; Pedological Processes; Soil Management; Soil Taxonomy; Ultisols; Vertisols; World Reference Base for Soil Resources (WRB)

1. INTRODUCTION

Ethiopia has a diverse geological structure and physiography that exhibit remarkable variety and mosaic of landscapes (Henricksen et al., 1984; Schluter, 2000). The country has the elevation range from 180 meters below sea level in Danakil depression and costal lowlands to interior highlands that reach 4260 meters in Semen Mountains. Climate varies from arid to perhumid. Varying combinations of elevations and climatic regimes have resulted in a large number of agro-ecological regions with contrasting physiographic elements and conditions for agricultural production. The diverse soil forming factors and pedogenic processes in turn give rise to different soil groups (Goebel et al., 1984; Hurni, 1998). The genesis and distribution of soils of Ethiopia are influenced by agro-ecological zones underlain by geology and physiography (Bruggeman, 1984; Henricksen et al., 1984).

Several studies have been conducted to figure out dominant factors controlling soil properties in different physiographic regions of Ethiopia (Gebrekidan et al., 2005; Yimer et al., 2006; Fritzsche et al., 2007; Wauw et al., 2008; Ali et al., 2010; Desalegn et al., 2015). The studies show that soil development along the main Ethiopian rift valley was influenced mostly by relief and climate. In Bale Mountain most of the soil properties were related to topographic aspect and vegetation communities. Topography controlled soil development and characteristics in Southern Ethiopia (Ali et al., 2010). Some studies were also undertaken to investigate the effect of parent materials and moisture regimes on soil development and characteristics. For example, in basalt dominated highland of Tigray of Northern Ethiopia, geology, mass movement and erosion predominantly influenced soil development and variability (Wauw et al., 2008). Esayas et al. (2006) also investigated the effect of ignimbrite and basaltic rocks on genesis and classification of soils in sub-humid tropical highland of Southern Ethiopia. They found formation of Oxisols under udic moisture regime from ignimbrite and basaltic rocks, and Ultisols and Alfisols under ustic moisture regime from ignimbrite parent materials. The studies showed that soil development, expression of pedogenic processes and properties varied with topography, climate, parent materials, vegetation, land use and local site characteristics across varying physiographic regions and agro-ecological zones. The humid physiographic regions of Western and Southwestern Ethiopia have contrasting features from other physiographic regions of the country. Soil developmental studies and properties in these regions are lacking.

The physiography of Western and Southwestern Ethiopian highland regions exhibit unique characteristics in terms of mountainous topography, severe dissection and incision of landforms. The regions receive high precipitation over 240 days per annum and include numerous humid agro-ecologies zones. Intensive network of rivers has exposed diverse rock units of variable lithology and chronology (Henricksen et al., 1984; Hurni, 1998). Various studies conducted in these regions have identified a great number of geomorphic processes involved in landform genesis and parent materials of varying origin and chronology (Henricksen and Wijntje-Bruggeman, 1984; Ayalew and Moore, 1989; Solomon and Mulugeta, 2000; Tadesse and Tsegaye, 2000; Tadesse, 2014.). Schists and gneisses of Precambrian Basement, Paleozoic-Mesozoic rocks, Tertiary volcanics and Quaternary sediments of Cenozoic periods are the major soil parent materials in the region (Ayalew and Moore, 1989; Solomon and Mulugeta, 2000; Tadesse and Tsegaye, 2000; Tadesse, 2014). Topography affects climate, vegetation, movement of materials and energy (Jenny, 1945). Landscape of Western and Southern Ethiopian highlands used to be covered with dense forest and now have become forest free. This is due to expansion of agriculture into marginal steep and forest lands due to population pressure and food insecurity. Almost all landscape positions have become under agricultural crop and livestock production. Land degradation, particularly soil erosion and chemical soil infertility, has become rampant (Conway, 2000; Sima, 2011; Deressa, 2013; Deressa et al., 2013; Oromia Rural Land and Environmental Protection Bureau, 2014a; Oromia Rural Land and Environmental Protection Bureau, 2014b; Siraj et al., 2015).

The soil potentials and vulnerabilities of different landscape positions determine the land use systems. Sustainable land use systems require proper land use planning, secure food production and conservation practices to counteract environmental degradation. Soil properties are the product of soil forming factors and pedogenic processes undergoing in landscapes (Schaetzl and Anderson, 2005). Understanding of pedogenic processes and soil properties are essential for land use planning and prerequisites for proper landscape management. Soil properties and pedogenic processes involved in landscape with multiple state factors (climate, parent materials and topography) can be best studied by soil-landscape interrelationship. A transect study along toposequence is one of the best ways to discern interrelationship between soil properties and landscape positions (Schaetzl, 2013). Land use related analysis and multiple aspects of landscape positions are the current approaches to investigate the poorly described pedogenic processes and soils properties in Western Ethiopia. Didessa watershed is identified as having a suitable landscape for studying the effect of multiple factors on genesis, properties and soil classification.

Lack of basic information on pedogenic processes and properties hamper addressing the current challenges of agriculture and environment in Didessa watershed. The first objective of the study was to describe the pedological processes, and morphological, physical and chemical properties of soils in Didessa watershed. The second objective was to classify the soil sequence in the watershed according to standard classification systems to share scientific information and recommend management requirements for sustainable soil uses. The study consisted of characterizing six benchmark profiles of representative landscape units, classification according to WRB (2014) and Soil Taxonomy (Soil Survey Staff, 2014) and discussion in the context of topography, parent materials and geochronology. Emphasis was put on land uses, as they reflect different management options for sustainable use of land resources and conservation of landscape.

2. MATERIALS AND METHODS

2.1. Description of the watershed and study transect

The location of Didessa watershed in Western Ethiopia is indicated in Fig. 1. Didessa watershed drains an area of 9,486 km^2. It is the tributary of Blue Nile which flows into North Western Ethiopia. The watershed covers 5.4% of the total area of Blue Nile and contributes 6.86 km^3 annual discharge corresponding to 10.7% of the total annual discharge of Blue Nile (Conway, 2000). The topographic map of the 52-km long route of the study transect that extends from 9°06’12.7180”N, 36°28’22.1868”E to 8°40’1.9920”N, 36°25’13.0308”E is indicated in Fig. 2. Twenty years climatic data of twelve metrological stations in and around Didessa watershed are summarized in Fig. 2. Mean annual rainfall of the stations varies from 1400 to 1920 mm and has a unimodal pattern of rainfall distribution. The length of growing period (LGP) in the watershed ranges from 180 to 300 days. Long term monthly temperature minima range from 11 to 16°C and temperature maxima range from 26 to 28°C with the average temperature from 19 to 23 °C. Three agro-climatic zones (ACZ), namely warm sub-humid lowland (180-240 LGP, 20-27.5 °C, 500-1300 m.a.s.l.), tepid sub-humid midland (180-240 LGP, 15-20 °C, 1500-2000 m.a.s.l.) and tepid humid highland (240-300 LGP, 15-20 °C, 2000-2685 m.a.s.l.) agro-climatic zones, exist in the watershed (Hurni, 1996). The elevation ranges between 845 and 2685 m.a.s.l., and is characterized by sequence of contrasted landforms at varying physiographic positions. The three major topographic positions are low, mid and highlands with elevation range of less than 1500, 1500-2000 and 2000-2685 m.a.s.l., respectively.

2.2. Methodology

2.2.1. Pedon description and sampling of soil horizons

Six pedons were opened along a transect in Didessa watershed. The locations of the soil profiles were selected based on elevation and slope contour lines as well as agroecologies and land uses. Pedons 2, 3 and 4 were opened in the highlands, pedons 1 and 5 were in the midland and pedon 6 was in the lowland. The surrounding landforms of pedons were described in terms of elevation, slope (positions, form and inclination), lithology, drainage class, landforms, micro-relief and erosion features according to Field Soil Description Guide (FAO, 2006). Standard pedons were opened and described in the field. Horizons, horizons boundaries (distinctness and topography), soil matrix colors, roots, soil structure and consistency, coatings and mineral concretions were also described (FAO, 2006). About 2 kg composite samples were collected from each horizon and air dried in properly ventilated room on plastic trays. The air-dried samples were sieved (2 mm mesh) and used for analysis. The analytical results are reported on the oven dry basis.

2.2.2. Soil analysis

Particle size analysis was done by the modified sedimentation hydrometer procedure of Bouyoucos (Kroetsch and Wang, 2006). Soil textural classes were read from the textural triangle (WRB, 2014). Clay contrast index (CCI) was calculated from percent clay contents in different horizons according to eq. 1 (Young, 1976; Khomo, 2008). The pH of the soils was measured using a pH meter by inserting the electrode into the supernatant of 1:2.5 ratio suspension of soil to liquid . The liquids used were distilled water (pH_{H2O}), 0.01 M $CaCl_2$ and 1 M KCl (pH KCl) according to the procedure outlined by Reeuwijk (1992). Soil organic carbon (SOC) was determined by the Walkley-Black procedure (Reeuwijk, 1992). Exchangeable cations (Ca, Mg, Na and K) and CEC were extracted by 1 M ammonium acetate at pH 7.0 (Reeuwijk, 1992). Exchangeable Ca and Mg in leachate were determined by AAS, and exchangeable K and Na were measured by flame photometer. Exchangeable acidity was extracted by 1 M KCl solution and determined titrimetrically (Bertsch & Bloom, 1996). Effective Cation Exchange Capacity (ECEC) was determined by summation of exchangeable cations (exchangeable acidity and bases). Saturation of exchange complex (SEC) with cations was determined as indicated in eq. 2. Percent base and acid saturations were calculated according to eq. 3 and eq. 4, respectively. The CEC of clay were calculated according to Yerima (1993) as indicated in eq. 5. It assumed that soil organic matter (SOM) has CEC of 200 $cmol_c\ kg^{-1}$ and mineral fractions coarser than clay do not have a significant CEC.

$$CCI = \frac{Clay\ in\ the\ upper\ horizon}{Maximum\ clay\ in\ profile} --- eq.1$$

$$SEC = \frac{ECEC}{CEC} * 100 --- eq.2$$

$$BS = \frac{\Sigma Ex.\,bases\ (Ca, Mg, Ka, Na)}{ECEC} * 100 --- eq.3.$$

$$AD = \frac{\Sigma Ex.\,Al + H}{ECEC} * 100 --- eq.4.$$

$$CECclay = \frac{(CEC\ of\ soil - OM * 200)}{Clay} --- eq.5$$

Where SEC=Saturation of Exchange Complex with cations, ECEC=Effective Cation Exchange by summation, CEC=Cation Exchange Capacity, BS=Base Saturation Percentage, AS= Acid Saturation Percentage, CCI=Clay Contrast Index, OM=Organic matter.

2.2.3. Statistical Analysis and Soil Classification

Software and Statistical Analysis: Map of the study watershed was made by ArcGIS software version 10 software and topographic map of the study transect was constructed using Global Mapper version 13. Correlation and regression analysis were carried out by IBM SPSS statistics version 20 software. P-values of 0.01 and 0.05 were used for the identification of statistically highly significant and significant differences, respectively.

Soil Classification and Clustering Analysis: The six pedons and horizons identified in the field were classified according to the U.S. Soil Taxonomy (Soil Survey Staff, 2014) and the WRB System (2014) which are non-numerical systems. Numerical classification was also carried out based on agglomerative hierarchical cluster analysis (Young and Hammer, 2000). Quantitative soil data were used in one analysis to include the effects of vertical profile differentiation. The technique arranged individual genetic horizons together into larger groups (classes) in such a way that individuals belong to small groups, the small groups belong to larger groups, and so on. The result of the hierarchical cluster analysis was displayed using dendrogram. Hierarchical cluster analysis was compared to pedon and horizon classification of U.S. Taxonomy and WRB system.

3. RESULTS AND DISCUSSION

3.1. Characterization of the Transect

Site characteristics around pedons in slope, permeability and water erosion were variable (Fig. 2). Pedons 1 to 4 were on contrasting elevation in highland whereas pedons 5 and 6 were on midland and lowland positions, respectively. Pedons 1 to 6 were on landscapes with slopes of 3, 3, 2, 5, 4, and 2% at shoulder, shoulder, summit, shoulder, backslope and toe slope position, respectively. All pedons 1 to 5 were well drained and pedon 6 was poorly drained. Severe erosion was observed at pedons 1 to 5, the intensity of erosion depending on slope class, slope form, position and land use. Water logging and gilgai micro relief were observed at pedon 6. Land uses at pedons 1 and 2 were coffee and eucalyptus plantation, respectively, pedons 3 to 5 represented annual arable field cropping with varying land use histories and at pedon 6 grassland and scattered woodland vegetation was growing (Fig. 2). Pedons 1, 2 and 4 were developed on lower basaltic rocks, pedon 3 was on basalt and pedon 5 on granitic gneiss, whereas pedon 6 was on outwash alluvium and colluvium (Fig. 2). Slope, clay mineralogy and land use contribute to differences in soil erosion, micro-relief (gilgai) formation and drainage classes. The slope controls the movement of matter and energy downslope and has minimal effect on summit, erosional effect on shoulder positions, transportational effect on middle slope position and depositional effect near the base of landscape (Schaetzl, 2013) and throughfall induces soil erosion. As the result of variation of landforms in terms of slope, mineralogy and land uses, pedons 1 and 2 had accelerated sheet and rill erosion, pedon 3 had sheet erosion, and pedon 4 had rill and gully erosion. Effects of land use, tillage and clearance of vegetation cover have intensified soil erosion through its effect on soil detachment, interception of potential energy of raindrops and reduction of running force of overland flow that was observed at pedons 4 and 5. The results were consistent with the impacts of topographic positions and land uses on materials and water movement at hillslope catena (Schaetzl and Anderson, 2005; Buol et al., 2011; Schaetzl, 2013).

3.1. Morphological Properties of Soils

The six pedons had well developed morphological characteristics (Table 1). The pedons had A-Bt horizon sequences. Pedons 1 and 6 had thin A_1 horizons with higher organic matter content than the other pedons. The thin A2 horizons which are higher in OM were formed from litter fall and deposition from forest coffee and grassland. Decomposition of OM and formation of humus in sites at pedons 1 and 6 is presumed to be accelerated by favorable soil moisture and temperature. The presumed high decomposition rate of OM resulted in a surface horizon low in OM content. Similarly, pedon 2 was situated within an eucalyptus plantation and there was not enough litter to form an O horizon due to lack of understory trees and insufficient litter biomass. Pedon 3 was located at the summit position of the slope and had a black A-horizon due to absence of erosion and lack of lateral loss of OM. Lower temperature and longer soil moisture might have caused addition of OM to exceed mineralization rate. Pedon 4 was in cultivated land, and tillage and erosion have truncated some part of the A-horizon. The B horizons in pedons 1, 2, and 5 started at greater depths than B horizons in pedons 3, 4, and 6 due to sola stability in the former. All surface horizons had diffuse smooth horizon boundaries. Pedon 1 had a gradual and clear horizon boundary at Bt related to higher biological activity in the upper horizon (A) and fibrous rooting system of understory trees. Pedon 2 had diffuse smooth boundaries throughout the solum attributed to deep rooting of densely populated eucalyptus planation and lack of understory shrubs which had an effect on uniform water infiltration, as well as solute and material transport down the solum depth. Pedons 3, 4 and 5 had diffuse, smooth horizon boundaries in Ap, which has been disturbed by tillage. Pedons 1 to 5 had gradual and diffuse smooth horizon boundaries in the middle and bottom (Bt) of pedons due to migration of solutes and fine material from the overlying eluvial horizon (A) and accumulated in underlying illuviation horizons (Bt) beneath, related to depth of wetting front and subsequent drying. Pedon 6 had a gradual smooth boundary in the upper and a clear smooth boundary in the lower horizon (Bt) due to grass roots in upper horizons and pedoturbation as shown by slickensides and pressure faces of angular and sub-angular blocky soil aggregates. Variation in horizon depth and boundaries reflected variation in pedogenic processes arising from differences in landform and land uses (Graham, 2006).

Wide variation in soil color hue from 10YR to 10R were observed in surface and subsurface horizons. Redness increased from top to bottom of sola, except at pedon 6 which had uniform 10YR hue. Horizon color hues were affected by mineral composition and increased color hue redness from 10YR to 10R was due to changes in types of coatings (Schaetzl and Anderson, 2005). Dark and brown colors at surface and subsurface are caused by decomposed OM and magnetite. The reddish brown (7.5YR to 5YR) and deep red (5YR to 2.5 YR or redder colors) are caused due to presence of ferrihydrite and hematite, respectively. The dark gray color in pedon 6 at lower bottom was caused by presence of secondary calcium carbonate. Soil color values and chroma increased with soil depth or increased with decreased humus content. There were marked soil color variations among pedons and horizons on different landscape positions. Pedons on mid to highland were redder both at surface and subsurface and pedons on summit and footslope positions were darker. Thus, landscape position and climate affected runoff, leaching, and deposition, accumulation and decomposition of SOM. Erosion had removed soil material from shoulder and backslope leaving behind light and thinner soils (Schaetzl, 2013). Accumulation of SOM at higher elevation and on summit positions and low mineralization had given rise to darker soil color meeting the requirement (redder than 7.5YR) of the chromic qualifier of WRB in pedon 3. Pedon 6 was black, qualifying as pellic. The dark colors were due to movement of materials and water from upper position to lower landscape positions and associated with higher organic matter content and higher soil moisture at lower position. These results agreed with the previously reported works at Ele and Delbo Wegene watersheds of Southern Ethiopia (Ali et al., 2010; Desalegn et al., 2015). They reported that the dark colors in surface and redder color in subsurface horizons were due to OM and Fe compounds, respectively. They also observed redder color on higher position and darker colors at lower position, attributed to movement of materials and water from upper to lower landscape and higher OM contents and higher soil moisture at lower positions.

Table 2 shows profile root distribution, soil consistence and soil structures. Moist and wet consistence increased in pedons 1 to 5 when going deeper in the soil profile. Moist consistence of surface horizons ranged from very friable to friable and firm to very firm subsurface consistence at pedon 6. Variations in consistence were attributable to high OM contents at surface and high clay contents in subsurface horizons. Surface horizons were slightly sticky to sticky and slightly plastic to plastic at pedon 1 to 5 and pedon 6 had very plastic and very sticky surface and subsurface horizons. The overall friable and slightly sticky to sticky and slightly plastic to plastic surface consistence showed that the soils were workable at moist and wet conditions at upper and middle landscape positions whereas at lowland position, workability becomes difficult due to firm soils and very plastic and very sticky soil conditions. Change in soil consistence from higher to lower topographic positions could be due to change in clay minerals as suggested by Velde and Meuniier (2008). The CEC of clay also suggested shifts in clay mineralogy from kaolinitic to smectitic from higher elevation to low elevation. At highland and midland, soil materials and solutes were transported down both horizontally and laterally from desilication site to areas of resilication. As concentration of siliceous acid increased, 1:1 layered clay minerals leached out from upper position presumed to be reverted slowly to 2:1 expanding smectite clay that is common in heavy clay (black cotton) soils at lower landscape position (Velde and Meuniier, 2008).

3.2. Physical Properties of Soils

The surface horizons had sandy clay loam to clay loam and the subsurface horizons had clayey textures (Table 3). However, pedon 6 had clayey texture which graded towards a sandy texture. Sand and silt fractions decreased while clay fractions increased towards middle bottom of pedons which is indicative of clay illuviation. Sand to clay, and silt to clay ratios decreased to middle bottom of pedons 1 to 5 and an irregular trend was observed in pedon 6 which indicates lack of clay migration. Clay translocation and enrichment fulfilled requirements for the argillic or argic subsurface horizons except at pedon 6 (Soil Survey Staff, 2014; WRB, 2014). Higher Clay Contrast Index (CCI) indicates lower textural differentiation while lower CCI indicates higher textural differentiation in the profiles. The clay enrichment was decreased in the following pedon order: 0.85 (pedon 6) <0.58 (pedon 4) <0.48 (pedon 2) <0.46 (pedon 3) <0.44 (pedon 5) <0.38 (pedon 1). The variations in degrees of clay enrichment were related to slope positions and land uses. In the pedon on steep slope arable cropping had induced gully erosion and tillage activities had removed the upper horizon, lowering of clay content. Small differences between the highest and lowest amounts of clay in pedon 6??? at foot slope position are attributed to active pedoturbation through shrink-swell phenomenon. The pedons on summit position had high clay enrichment ratios due to minimum erosion. Coffee and eucalyptus plantations induced removal of clay by throughfall erosion and chelation, which preserved coarse texture. These results agreed with results from Ele and Delbo Wegene watersheds of Southern Ethiopia (Ali et al., 2010; Desalegn et al., 2015). They observed clay enrichment in steeper slope due to removal of finer particles and vertical clay migration in backslope positions. Negassa and Gebrekidan (2004) also reported variations in surface texture in cultivated, grazing and virgin forestland in Alfisols in Bako area of Western Ethiopia. They observed coarser textured soils in intensively cultivated and abandoned land which they attributed to removal of finer soil particles through sheet and rill erosion. The average sand, silt and clay contents of surface soils were 44, 20 and 36% respectively. These indicated that the present soils contained more sand, and less silt and clay compared to the average sand (17%), silt (32%) and clay (50%) contents of 125 soils collected from Ethiopian croplands (Sillanpää, 1981). The difference is explained by variation in mineralogical composition, climatic conditions and landform characteristics in the different physiographic regions of Ethiopia. The parent materials in most of North West of the Ethiopian Rift System are predominantly trap series basalts of uniform composition which produce fine texture upon weathering as compared to granitic rocks that produce coarse textured soils (Henricksen and Wijntje-Bruggeman, 1984; Ayalew and Moore, 1989; Solomon and Mulugeta, 2000; Tadesse and Tsegaye, 2000; Tadesse, 2014). Several studies have revealed that similar soils developed on trap series basalts in less humid regions in Southern Ethiopia, North Western margin of Rift Valley, and Central Ethiopia with higher proportion of clay fraction in both surface and subsurface horizons (Negassa, 2001; Isayas et al., 2006; Fritzsche et al., 2007; Abera, 2016). Moreover, development of dissimilar soils such as Vertisols, Luvisols and Acrisols on varieties of parent materials including basalts, sandstones, granites, dolerite intrusions and granites intercalated with limestone in Southern Eastern, North Eastern, North Western and Central Ethiopia with higher proportion of clay both in surface and subsurface horizons were reported (Henricksen and Wijntje-Bruggeman, 1984).

3.2. Coatings and Mineral Concretions

Table 4 indicates clay and humus coating on ped faces and concretions at different sola depths. Mineral concretions were observed in pedons 1 to 3 and 6. Pedon 1 and 2 had few to common clay and humus coatings at 100-200 cm depth. Pedon 3 had clay and humus coating at 75-120 cm and 120-200 cm. Pedon 4 had few to common clay and humus coatings at 80-200 cm and pedon 5 had few to abundant clay and sesquioxide coatings at 50-200 cm solum depth. Pedon 6 had few to many clay and humus coatings at depth 15 to 140 cm. Pedons 1 to 3 had mineral concretions and pedon 6 had secondary $CaCO_3$. The coatings and concretions showed clay, sesquioxide and humus migration from upper eluvial zones to illuviation zones. Secondary synthesis and weathering of primary minerals in B horizons could have contributed to accumulation of enriched zones (Velde and Meunier, 2008; Buol et al., 2011; Soil Survey Staff, 2014). Differences in the abundances of coating and concretions were connected to slope positions and land uses (plantation and tillage) which would have affected lateral and horizontal movements of solutions and plasma. Lack of concretions in pedon 4 and 5 might be due to instability of surface layers favoring horizontal and lateral movements of clays and humic materials. Studies at Ele and Delbo Wegene watersheds of Southern Ethiopia (Ali et al., 2010; Desalegn et al., 2015) did not report any observable clay coatings and concretions. This could be due to variation in climate such as precipitation and length of growing period (Fig. 2) as the current study was in the wettest part of Ethiopia where the ample precipitation had leached clay and humus down the pedons. Owing to the mineral coatings and concretions, the pedons 1 to 5 get a ferric qualifier and pedon 6 gets a calcic principal qualifier in WRB (2014) classification system for the third level classification. Due to the cutanic features observed in pedons 1 to 5, they all get the cutanic qualifier.

3.3. Soil Reaction and Composition of Exchange Complex

Table 5 and Table 6 show soil reaction and composition of the exchange complex. Soil pH_{H2O} in pedons 1 to 5 was acidic and acidity decreased down the pedon except pedon 6. Pedon 6 had acidic to alkaline reaction and pH_{H2O} increased from 6.3 to 8.5 with depth due to presence of $CaCO_3$ in the Bk horizon. Similar pH_{H2O} trend with depth was reported by Ping et al. (2013) along moisture and elevation gradients in Puerto Rico. They observed higher pH in moist lowland and lower pH in moist upland forest soils. The pH_{CaCl2} which measures soil reaction (active acidity) in rhizosphere at soil-root interface was acidic in pedons 1 to 5. Pedons 1, 3 and 6 had more or less increasing pH_{CaCl2} down pedon depth while pedons 2, 4 and 5 had lower acidity at the middle of the pedon. The values of pH_{H2O} were greater than those of pH_{CaCl2} in all pedons. The pH_{KCl} measures potential acidity on colloidal exchange complexes. Pedons 1 to 5 were acidic and the potential acidity increased with depth. Pedon 4 had a uniform acidity throughout the profile. Pedon 5 had lower pH_{KCl} in the middle horizon. Variations in pH_{KCl} in pedons and horizons showed shifts in compositions of colloidal exchange complexes (Hendershot et al., 2006; Pansu and Gautheyrou, 2006). In this study, there were no constant differences between $pH_{H2O-KCl}$ and $pH_{CaCl2-KCl}$ and the difference varied from pedon to pedon. The $pH_{H2O-KCl}$ ranged from 0.4 to 1.6 with the average difference being 1.2 pH units. Similarly, the $pH_{CaCl2-KCl}$ varied from pedon to pedon but was more uniform within pedon. ΔpH (pH_{H20}-pH_{KCl}) was positively indicative of higher negative charge density and higher CEC than anion exchange capacity and sign of high level of extractable Al. Large ΔpH as in pedon 2 to 6 suggests that these pedons are high in extractable Al which buffers soil solution and exchangeable acidity upon reclamation by application of liming materials (Uehara and Gillman, 1981). Similar positive ΔpH at Delbo Wegene watershed of Southern Ethiopia has been documented by Ali et al. (2010). Differences in ΔpH indicate strong variation in soil CEC and variation in the degree of pedogenesis in the stuied transect.

There was a significant negative linear correlation ($r=-0.87$, $p<0.025$) between topsoil pH_{KCl} and elevation. However, topsoil pH_{CaCl2} ($r=-0.78$, $p=0.069$) and pH_{H20} ($r=-0.60$, $p=0.21$) and ΔpH (pH_{KCl}-pH_{H2O}) were not significantly correlated with elevation. Subsurface pH_{H2O} ($r=-0.65$, $p<0.00$), pH_{CaCl2} ($r=-0.74$, $p<0.00$) and pH_{KCl} ($r=-0.76$, $p<0.00$) were correlated with elevation. Lack of significant correlation between surface soil pH_{H2O} and pH_{CaCl2} might be due to dominance of local relief features such as slope, soil erosion and tillage practices. The significant negative correlation of topsoil pH_{KCl} with elevation indicated an increase of exchangeable acidity with elevation. The decrease of subsurface pH with increased elevation cam be explained by increased leaching of basic cations. Similar to the soil system, the chemistry of spring water and rivers in Southwestern and Western Ethiopia also reveal that the pH, total dissolved solids, cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) and anions (HCO^{3-}, $SO4^{2-}$) increase from highlands to lowlands (OWWDSE, 2017). Similar results were also reported by Ping et al. (2013) in Puerto Rico along elevation and moisture gradients in upland and lowland forests. They reported that lowland and floodplains had higher pH and higher base saturation while upland soils had lower pH and lower base saturation due to leaching of cations associated with high precipitation in upland. Moreover, increasing values of pH with depth were observed due to increased leaching of surface horizons in upland while soils at low elevation had higher pH throughout the pedon depth. The average surface soil pH_{H2O} and pH_{CaCl2} were 5.3 and 4.6. These were lower than the average pH_{H2O} and pH_{CaCl2} of Ethiopian cropland soils which were 6.42 and 5.75, respectively (Sillanpää, 1982).

CEC of pedons varied with vertical depth and from site to site along the toposequence. CEC decreased down the depth in pedons 1 to 5 except pedon 3 located on summit slope position. This particular soil had irregular trends of CEC related to zones of eluviation and illuviation as high infiltration leached out cations from the E horizon and there was limited lateral movement of plasma. CEC in pedon 6 at foot slope position increased with depth. Exchangeable Ca in pedon 1 to 3 followed eluvial-illuvial patterns. The average surface CEC of the study soils was 38 cmolc kg^{-1} soils which is lower than the CEC range of Ethiopian cropland soils from 48 to 79 cmolc kg^{-1} due to higher clay contents (Sillanpää, 1982). Ca in pedon 4 to 5 showed decreasing patterns with depth due to biocycling and erosion. In pedon 6, Ca showed increasing patterns. Mg in pedon 1 to 3 followed a similar trend as Ca but in pedon 6 there was a decreasing trend. The average exchangeable Ca, Mg, K, and Na contents of surface soils were 9.8, 3.9, 0.7, and 0.1 cmolc kg^{-1} soils.

Sum of exchangeable bases in pedons showed irregular trends with depth. Sum of exchangeable bases decreased in eluvial and increased in illuvial zones in pedon 1 to 3 while exchangeable bases in pedon 6 showed decreasing trends and irregular pattern. CEC, exchangeable bases and ECEC showed clear altitudinal patterns. CEC ($r=-0.66$, $p<0.01$), Ca ($r=-0.81$, $p<0.01$), Mg ($r=-0.56$, $p<0.01$), Na ($r=-0.38$, $p<0.01$) and sum of exchangeable bases ($r=-0.81$, $p<0.01$) were negatively correlated with elevation whereas exchangeable K was not significantly correlated with elevation. The CEC of soils had clear altitudinal pattern and pH_{CaCl2} (adjusted $R^2=0.97$; $P=0.00$), pH_{CaCl2} and SOM (adjusted $R^2=0.98$; $p=0.044$) were parameters which explained much of the variation of CEC. Similar results of CEC along elevation and moisture gradients were reported by Ping et al. (2013) in Puerto Rican forest soils. Both clays and SOM contribute to the CEC of soils. They reported that CEC values in upland soils were higher in surface horizons followed by in A-horizons and lowest in B horizons. The CEC of these soils was closely associated with SOM in upland ($R^2=0.89$) and lowland soils ($R^2=0.97$). The CEC that was attributable to SOM of pedons decreased with depth and the trends with depth are related to land use. In pedons 1 to 5, the CEC of clays decreased with depth of the profile, while in pedon 6, the CEC of clays increased with depth. The variation in trends of CEC of the clay is attributed to the clay mineralogy. The CEC of the clay fraction in pedons 1 to 5 was similar to what was found by Melese et al. (2015) in Farta District where the analyzed clay mineralogy was predominantly kaolinitic with some smectite and illite. Pedon 6, with its high CEC, definitely deviates from our other pedons and likely has smectitic clay mineralogy. Desaturation (leaching) percentage of exchange the complexes showed that pedons 1, 2 and 5 were leached and had lower saturation with exchangeable base cations. Exchange complexes of pedons 3 and 4 apparently had a base saturation greater than 100% (sum of bases exceeded CEC) in illuvial horizons. In the surface horizon of pedon 6 the sum of base cations also exceeded the CEC in surface horizon but in the subsurface horizons the base saturation waslower than 100%. Besides leaching of cations in pedon 1, acidic cations (Al and H) dominated the exchange complex, giving rise to low base saturation. Exchange complexes in pedons 2 to 6 were dominated by basic cations and had a higher base saturation.

3.4. Pedological Processes

Pedological processes along the toposequence with subsequent soil properties are summarized in Table 7. Melanization produced dark to black surface A-horizons in all pedons at all landscape positions. Favorable moisture regime and cool temperature at higher elevation (pedon 3) accumulated humus and formed black colored A-horizon and chromic color in the subsurface horizon. Chelation (cheluviation) of Fe compounds by dissolved organic acids, translocation with percolating water and precipitation where percolating water stops formed dark red horizons in pedon 1 to 3. The organo-mineral complexes were not leached from soil profile because of limited lateral movement of percolating water as the result of flat to gently sloping topography in these land units. Reduction and subsequent oxidation of ferrous iron to ferric iron in all landscape units was observed in the form of coating on ped faces with the exception at low topographic position.

Weathering of iron bearing minerals release ferric iron from primary minerals followed by dispersion of iron oxides. The progressive oxidation or hydration and translocation of iron in the soil profile are conducive to brown, reddish brown and red colors. The oxidized and translocated iron in pedons 1 to 3 formed concretions because of limited flow of percolating water. Percolating water rich in dissolved iron was observed in pedon 4 and 5, caused by lateral percolating water and there were no observable iron concretions in the sloping land units.

Melanization, cheluviation (chelation) of organo-mineral substances, oxidation of iron, braunification, rubification, ferrugination, leaching of iron compounds and cations, clay translocation, de-alkalization, and acidification were the major pedological processes in the upland soils. Erosion was also observed at shoulder slope positions. Melanization, calcification and pedoturbation (vertization) were the conspicuous pedological processes in the low lying topographic position at footslope in the landscape. Clay translocation from eluvial to illuvial horizons formed argic (argillic) horizons in all pedons except pedon 6. Dealkalization process removed basic cations and acidification processes acidified the landscape units with the exception of pedon 6. Removal of calcium by decalcification in the upland removed calcium with percolating subsurface and surface water and deposited calcium rich water in the low lying topographic position. Upon drainage of percolation water, calcification process formed calcium carbonate in the subsurface horizons. This formed a calcic horizon. Pedoturbation (vertization) process formed Vertisols with wedge shaped, massive, and polished aggregates with tapering edge, shrink swell properties and gilgai micro-relief formation at low lying topographic position at foot slope position with imperfect drainage.

3.5. Horizon development and classification

Surface horizon of pedon 1 was an umbric epipedon while pedons 2 to 6 were mollic according to Keys to Soil Taxonomy (Soil Survey Staff, 2014). Pedons 1 to 5 had argillic (Soil Survey Staff, 2014) and argic (WRB, 2014) subsurface horizons while pedon 6 had developed vertic and calcic subsurface horizons (Soil Survey Staff, 2014; WRB, 2014). Distinctness of pedons and their horizons were indicated in the hierarchical cluster analysis (Fig. 3). The dendrogram showed seven distinct clusters of horizons. Umbric and argillic horizons of pedon 1 were more alike but separated from the rest of horizon clusters. Mollic and vertic horizons of pedon 6 were the second distinct cluster where A, B_1 and B_2 horizons were more alike than the BC horizon of pedon 6. Umbric and argillic horizons in pedon 3 were the third cluster in which B_1 and B_2 were more alike. Ap horizon of pedon 3 was the fourth distinct cluster in dendrogram. A-horizons of pedons 2, 5, 6 and horizon of B1 of pedon 3 made the fifth distinct cluster and were more alike as compared to rest of horizons. Argillic B horizons of pedons 2 and 5 made the sixth cluster and were more alike. The argillic B horizons of pedons 2, 5 and 6 made the seventh distinct clusters which were more alike in dendrogram. The cluster analysis indicated that pedogenesis and/or horizon forming processes in toposequence were categorized into seven distinct clusters. Pedogenesis in pedons 1 and 6 were very distinct. Pedogenesis in horizons of pedon 6 was less alike with horizons in pedon 1. Pedogenesis in pedons 2, 3, 4 and 5 were more alike than in pedon 6. The numerical hierarchical cluster analysis revealed that pedological properties in B horizons in pedons 2, 4, and 5 were more alike while the corresponding A-horizons were more alike and distinct from their underlying B horizons. Thus, numerical cluster analysis based on quantitative soil properties detected intra and inter variability of pedons and strongly supported the standard classification systems. According to Soil Taxonomy (Soil Survey Staff, 2014), three soil orders namely Ultisols, Alfisols and Vertisols were identified, the lower level classes being summarized in Table 8. Using the WRB (2014) system, Alisols, Luvisols and Vertisols were identified. Both classifications systems provided very similar information at the highest level of taxonomic units (Ultisols-Alisols, Alfisols-Luvisols, and Vertisols) indicating clay illuviation, soil acidity, and/or clay mineralogy.

In Soil Taxonomy, soil moisture regime, presence of oxides and associated soil colors were used to group soils at the suborder and great group level. While at second level of classification in the WRB (2014) system, principal and supplementary qualifiers were used to further provide detailed information about the soil properties. The WRB (2014) names provided more detailed information related to land management than the Soil Taxonomy. Soil color was also expressed with principal qualifiers, as well as the presence of pedogenic calcite in pedon 6. The numerical hierarchical cluster analysis revealed that pedological properties in B horizons in pedons 2, 4, and 5 were more alike while the corresponding A-horizons were more alike and distinct from their underlying B horizons. Thus, numerical cluster analysis based on quantitative soil properties detected intra and inter variability of pedons and strongly supported the standard classification systems. The supplementary qualifiers of the WRB system also indicated texture, characteristics of the exchange complex and the presence of cutans, which actually is also expressed by the RSG. It is surprising that, in spite of rather low pH, the pedons 1 to 5 qualify as hypereutric. Therefore, discussion of these criteria of the WRB system might be needed.

Similar study was carried out in less humid environment in the main Ethiopian Rift Valley escarpment which was characterized by range of elevation between 1900 to 3200 m.a.s.l., mean annual temperature between 19 to 13°C and annual precipitation between 800 to 1600 mm (Fritzsche et al., 2007). They reported that Mazic Vertisols were identified at low elevation in semiarid environment. At the highest level of generalization, Mazic Vertisols in the Rift Valley escarpment are similar with the Vertisols in humid environment in Didessa watershed. Similarly, Nitic Umbric Alisols were identified at humid environment at higher elevation in the Ethiopian Rift Valley escarpment. At the first level, the Alisols identified in Main Ethiopian Rift Valley escarpment are similar to Alisols identified in higher elevation with humid environment in the Didessa watershed. Other soil groups such as Mollic Nitosols, Humic Umbrisols and Mollic Cambisols were also identified in Rift Valley system but lacking in the toposequence of Didessa watershed in humid environment.

Soils in Didessa watershed were very deep, highly leached, redder and acidic due to high degree of weathering. They are characterized by accumulation of clay coating and mineral concretion of oxides and hydroxides of Al and Fe as evidenced by color redness, the existence of cutanic features and concretions. Soil development in both Main Rift Valley escarpment and Didessa watershed were controlled primarily by relief and climate. Ultisols and Alfisols found at Didessa toposequence are also found in Southern Ethiopia, developed on quaternary ignimbrites in Ustic moisture regime (Isayas et al., 2007). Alfisols (Chromic Luvisols) and Pellic Vertisols were also found in humid Central, Eastern and Northern Ethiopia (Henricksen et al., 1984). Alfisols and Ultisols found in the Didessa toposequence were at a more advanced stage of weathering than Ultisols and Alfisols in other regions of Ethiopia as evidenced by high degree of expression of soil morphology, clay coatings, mineral concretions, chemical compositions and physical properties of soils.

The parent materials for pedons 1 and 2 were lower tertiary basalts (Wollega Basalt) formed during Miocene to Oligocene age (32.8 to 21.2 Ma). Both pedons were located in humid old landform with comparable litho-chronologies. Pedon 1 was at a more advanced stage of soil development than pedon 2 that could be due to lack of accurate dating of the chronology and pedon 2 might be formed on less stable land form than pedon 1. Alternatively, the difference might arise from the land uses in which decomposition of OM and release of dissolved OM might have caused more leaching and depletion of nutrients in pedon 1. Parent material for pedons 2 and 4 were lower tertiary basalt and for pedon 5 granitic gneiss of Precambrian basement rock with varying physical and chemical properties as well as chronology. Despite difference in parent materials, pedon 2 to pedon 5 were classified in the same RSG or soil order as Luvisols or Alfisols, indicating that other soil forming factors such as climate had an overriding effect on pedogenic processes. The elevation ranged from 1273 m to 2543 m.a.s.l., and the total annual precipitation and the length of the growing period increased while temperature decreased with elevation (Fig. 2). The agro-climates ranged from warm subhumid to tepid humid highland (Fig.1). Pedon classifications and cluster analysis showed that much of the variation in the identified RSGs is not explained by variations in parent materials. On the other hand, the soil classifications and hierarchical cluster analysis clearly showed that the effect of elevation induced variation in climatic parameters on soil types and pedogenesis in the study toposequence. Advanced soil development was observed at intermediate elevation, transition to the highland, as low and high temperature and moisture extremes in the lowland and highland limit pedogenesis.

4. CONCLUSIONS AND RECOMMENDATIONS

Soil classification using U.S. Soil Taxonomy, WRB and numerical hierarchical cluster analysis provided comparable results. Ultisols (Alisols), Alfisols (Luvisols) and Vertisols were elements of soil catena identified along the toposequence. However, numerical hierarchical cluster analysis detects more subtle homogeneity and heterogeneity of the soil horizons based on quantitative soil properties. All soils involved in the current study were at an advanced stage of development. The soil development and properties were controlled by relief characteristics and climate. The pattern of chemical properties and taxonomic units were attributed largely to the regional topographic positions, local hillslope positions, climate and land use. The effect of parent materials on soil development varied with elevation. In the low elevation position, Vertisols were developed on alluvium and colluvium parent materials. At the higher elevation, Ultisols (Alisols) were developed on tertiary basalt whereas Alfisols (Luvisols) were developed on tertiary basalts and granitic gneiss. In the midland and highland, the effect of local topography seems to have a more dominating effect on the soil development than parent materials. Basic cations in soils of highland and sloping land were highly depleted by leaching, and the soils had become highly acidic and highly oxidized as evidenced by coatings and concretions of iron oxides and hydroxides. CEC and exchangeable bases were negatively correlated with elevation and variation in CEC along elevation gradients was largely explained by pH, with little contribution by SOM.

Ultisols were found on basaltic parent material, Alfisols on basaltic and granitic gneiss and Vertisols were found on alluvium and colluvium parent materials indicating topography and land uses as major causes for soil variation along the transect. Variations in pedogenic processes have resulted in variation in soil properties and soils types that require different management and land use plans for sustainable uses. Alisols - Ultisols that are at an advanced stage of weathering could be used to grow acidity tolerant crops or need to be limed to benefit crop production. Luvisols that are at an intermediate stage of weathering had inherent fertility, contain high activity clays and have low Al saturation have moderate to good potential for agriculture with proper rate of lime, fertilization and rigorous erosion control. Vertisols which have a high chemical fertility and a considerable agricultural potential have poor physical properties. This causes serious management constraints related to shrink-swell properties that make tillage problematic and cause water logging. The water dynamics of Vertisols could be improved through management practices such as the use of beds, ridges and furrows to protect crops from water logging and contour cultivation to improve infiltration.

The elevation, relief characteristics, lithology, agro-ecology and land uses covered by the current study are typical of much of the Western and Southwestern Ethiopia. Thus, the transect serves as a model of soil development and soil management in humid Western Ethiopia. This study suggests that a soil sequence within a catena requires different management options and land use plans for sustainable land use.

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Table 1: Pedon depth, horizons, color and structure description of studied pedons

Pedon	*Horizons*	*Depth, cm*	*HB*		*Color (moist)*	
			D	*T*	*Nt*	*Standard name*
Pedon 1	O	0-20	-----	-------	5YR3/2	Dark reddish brown
	A	20-50	Diffuse	Smooth	5YR3/2	Dark reddish brown
	B	50-100	Gradual	Smooth	5YR3/3	Dark reddish brown
	Bt1	100-150	Clear	Smooth	2.5YR4/4	Reddish brown
	Bt2	150-200	Clear	Smooth	2.5YR5/6	Red
Pedon 2	A	0-20	-----	-----	7.5YR3/2	Dark brown
	AB	20-50	Diffuse	Smooth	7.5YR3/3	Dark brown
	Bt1	50-100	Diffuse	Smooth	5YR3/4	Dark reddish brown
	Bt2	100-150	Diffuse	Smooth	2.5YR4/6	Reddish brown
	Bt3	150-200+	Diffuse	Smooth	2.5YR4/4	Reddish brown
Pedon 3	Ap	0-25	----	----	10YR3/2	V. dark grayish brown
	Bt	25-75	Diffuse	Smooth	10YR2.5/2	Very dark brown
	Bt1	75-120	Gradual	Smooth	7.5YR4/4	Brown
	Bt2	120-200+	Diffuse	Smooth	5YR4/4	Reddish brown
Pedon 4	Ap	0-30	----	----	7.5YR3/3	Dark brown
	Bt1	30-80	Diffuse	Smooth	5YR3/3	Dark reddish brown
	B22	80-125	Gradual	Smooth	2.5YR3/6	Dark red
	Bt3	125-200+	Diffuse	Smooth	10R4/6	Red
Pedon 5	Ap	0-20	----	----	7.5YR3/2	Dark brown
	AB	20-50	Diffuse	Smooth	7.5YR4/4	Brown
	B1	50-100	Clear	Wavy	5YR4/4	Reddish brown
	B2	100-150	Clear	Wavy	2.5YR4/6	Red
	B3	150-200+	Diffuse	Smooth	10R4/6	Red
Pedon 6	O	0-15	----	----	10YR2/1	Black
	A	15-40	Gradual	Smooth	10YR2/1	Black
	B1	40-80	Gradual	Smooth	10YR2/1	Black
	B2	80-130	Clear	Smooth	10YR4/1	Dark gray
	BC	130-170	Clear	Smooth	10YR7/1	Light gray

HB=horizon Boundary, D=Distinct, T= Topography, Nt=Notations

Table 2: Description of roots, structure and consistence of studied pedons

Pedon	Horizon	Depth, cm	Roots		Structure			Consistency	
			A	Sz	*Gd*	*Sz*	*Tp*	Mt	Wt
PR-01	O	0-20	M	MO	WE	FM	GR	VFR	SPL/SST
	A	20-50	M	MO	WE	FM	GR	FR	SPL/SST
	B	50-100	Cn	CO	ST	FM	SB	FI	PL/ST
	Bt1	100-150	F	Fi	ST	FM	SB	FI	PL/ST
	Bt2	150-200+	-	-	WE	FM	MA	VFI	SPL/SPL
PR-02	A	0-20	M	MO	MO	MC	SB	FRFI	PL/ST
	AB	20-50	M	MO	MO	MC	SB	FRFI	PL/ST
	Bt1	50-100	C	CO	ST	MC	SB	FIVFI	PL/ST
	Bt2	100-150	C	CO	ST	C	SB	FIVFI	PL/ST
	Bt3	150-200+	F	F	ST	C	SB	FIVFI	VPL/VST
PR-03	Ap	0-25	Fe	Fi	WM	FM	SB	FR	SPL/SST
	Bt	25-75	Fe	Fi	WM	FM	SB	FR	PL/ST
	Bt1	75-120	-	-	M	MC	SB	FI	VPL/VST
	Bt2	120-200+	-	-	M	MC	SB	VFI	VPL/VST
PR-04	Ap	0-30	CO	CO	MO	MC	SB	VFRFR	SPL/SST
	Bt1	30-80	CO	CO	MO	MC	SB	VFRFR	SPL/SST
	B22	80-125	Fe	Fi	ST	C	SB	FI	PL/ST
	Bt3	125-200+	-	-	ST	C	SB	FI	PL/ST
PR-05	Ap	0-20	M	MO	MO	FM	SB	FR	SPL/SST
	AB	20-50	C	CO	MOST	FC	SB	FR	SPL/SST
	B1	50-100	F	Fi	ST	MC	SB	FI	PL/ST
	B2	100-150	-	-	ST	MC	SB	VFI	VPL/VST
	B3	150-200+	-	-	ST	MC	SB	FRI	VPL/VST
PR-06	O	0-15	M	MO	MO	MC	SAB	FI	VST/VPL
	A	15-40	C	CO	ST	MC	SAB	FI	VST/VPL
	B1	40-80	C	CO	ST	C	AW	VFI	VST/VPL
	B2	80-130	Fe	Fi	ST	C	AW	VFI	VST/VPL
	BC	130-170	-	-	WE	FM	RS	LO	ST/PL

Gd=Grade, Sz=Size, Tp=Type, MO=Moderate, ST= Strong, SB=Subangular Blocky, AW=Angular Blocky (Wedge-Shaped), RS= Rock Structure, M=Medium, C=Coarse, FM=Fine to Medium, FI= Firm, VFI=Very Firm, LO=Loose, MA=Massive, A=Abundance, Sz=Size, S= Sand, Si=Silt, C=Clay, CT= Textural Class, Mt=Moist, Wt=Wet, M=Many, Cn=Common, Mo=Moderate, Fe=few, Fi=Fine, SCL=Sandy Clay Loam, L=Loam, CL=Clay Loam, SC=Sandy Clay, VFR=Very Friable, VFRFR=Very Friable to Friable, FR=Friable, FI=Firm, VFI=Very Firm, FRFI=Friable to Firm, FIVFI=Firm to Very Firm, SPL=Slightly Plastic, SST=Slightly Sticky, PL=Plastic, ST=Sticky, VPL=Very Plastic, VPL=Very Plastic

Table 3: Some physical properties of the studied pedons along toposequence

Pedon	Horizon	Depth, cm	S	Si	C	Textural Class	S: C	Si:C	CCI
Pedon 1	O	0-20	59	19	22	SCL	2.68	0.86	0.38
	A	20-50	51	23	26	SCL	1.96	0.88	
	B	50-100	49	19	32	SCL	1.53	0.59	
	Bt1	100-150	31	11	58	C	0.53	0.19	
	Bt2	150-200	37	11	52	C	0.71	0.21	
Pedon 2	A	0-20	45	25	30	SCL	1.50	0.83	0.48
	AB	20-50	47	9	44	SC	1.07	0.20	
	Bt1	50-100	31	13	56	C	0.55	0.23	
	Bt2	100-150	29	9	62	C	0.47	0.15	
	Bt3	150-200+	31	7	62	C	0.50	0.11	
Pedon 3	Ap	0-25	43	33	24	L	1.79	1.38	0.46
	Bt	25-75	31	25	44	C	0.70	0.57	
	Bt1	75-120	35	23	42	C	0.83	0.55	
	Bt2	120-200+	29	19	**52**	C	0.56	0.37	
Pedon 4	Ap	0-30	41	25	34	CL	1.21	0.74	0.58
	Bt1	30-80	33	13	54	C	0.61	0.24	
	B22	80-125	33	7	60	C	0.55	0.12	
	Bt3	125-200+	31	5	64	C	0.48	0.08	
Pedon 5	Ap	0-20	43	27	30	CL	1.43	0.90	0.44
	AB	20-50	25	7	68	C	0.37	0.10	
	B1	50-100	25	11	64	C	0.39	0.17	
	B2	100-150	31	15	54	C	0.57	0.28	
	B3	150-200+	35	19	46	C	0.76	0.41	
Pedon 6	O	0-15	45	21	34	SCL	1.32	0.62	0.85
	A	15-40	47	15	38	SC	1.24	0.39	
	B1	40-80	49	11	40	SC	1.23	0.28	
	B2	80-130	53	11	36	SC	1.47	0.31	
	BC	130-170	69	7	24	SCL	2.88	0.29	

S=sand, Si=Silt, C=Clay, S: C=Sand to Clay ratio, Si: C=Silt to Clay ratio, CCI=Clay Contrast Index

Table 4: Description of coatings and mineral concretions of study pedons

Pedons	Depth, cm	Coating					Mineral Concretion						
		A	Ct	Nr	Fm	Lt	A	Kd	Sz	Sp	Hd	Nr	Cr
Pedon 1	100-150	C	Faint	CHS	Cont.	P	-	-	-		-		
	150-200+	-	-	-	-	-	M	N	FM	R	H	CSQ	YB
Pedon 2	100-150	F	Faint	CHS	Discont.	P	C	N		R	H	CSQ	B
	150-200+	C	Faint	CHS	Discont.	P	C	N		R	H	CSQ	B
Pedon 3	75-120	F	faint	CHS	Discont.	P	F	N	FM	I	S	CS	B
	120-200+	C	distinct	CHS	Cont.	P	C	N	FM	I	S	CS	B
Pedon 4	80-125	F	Faint	CHS	Cont.	P	-	-	-	-	-	-	-
	125-200+	C	Faint	CHS	Cont.	P	-	-	-	-	-	-	-
Pedon 5	50-100	F	Faint	CS	Cont.	P	-	-	-	-	-	-	-
	100-150	A	faint	CS	Cont.	P	-	-	-	-	-	-	-
	150-200+	A	faint	CS	Cont.	P	-	-	-	-	-	-	-
Pedon 6	15-40	F	Faint	CH	Cont.	P	-	-	-	-	-	-	-
	40-80	C	Faint	Clay	Cont.	P	C	SS	F	I	Soft	K	White
	80-130	M	Faint	Clay	Cont.	P	M	SS	M	I	Soft	K	White
	130-170	-	-	-	-	-	D	RF	C	I	H	K	White

A=abundance, Ct=contrast, Nr=nature, Fm= form, Lt=location, Kd=kind, Sz=size, Sp=shape, Hd=hardness, Cr=color, M= many, C= common, F=few, CHS=clay, humus, sesquioxides, P=pedface, FM=fine to medium, N=nodules, R=round, H=hard, CSQ=clay, sesquioxides, silica, FC=fine to coarse, MC=medium to coarse, S=sesquioxides, B=black, YB=yellowish brown, I=irregular, S=soft, CS=clay, sesquioxides, A=abundant, CH=clay, humus, D=dominant, RF= residual rock fragment, SC=soft segregation, K=carbonate, Discount.= Discontinuous, Cont. = Continuous

Table 5: Soil reaction (pH), organic carbon, CEC and exchangeable acidity of study pedons

Pedon	Horizon	Depth, cm	pH 1:2.5(V/W)			ΔpH		CEC	Exchange acidity	OC
			H20	$CaCl_2$	KCl	H20-KCl	CaCl2-KCl	Cmolc/kg		%
Pedon 1	A1	0-20	4.2	3.9	3.8	0.4	0.1	41.5	10.0	7.7
	A2	20-50	4.4	4.0	3.9	0.5	0.1	37.6	8.8	6.6
	B	50-100	4.8	4.0	3.9	0.9	0.1	36.7	9.5	5.6
	Bt1	100-150	4.5	4.0	3.9	0.5	0.1	30.3	8.5	2.3
	Bt2	150-200+	4.6	4.2	4.1	0.5	0.1	22.5	4.5	1.0
Pedon 2	A	0-20	5.5	4.9	4.4	1.1	0.5	42.7	0.3	6.1
	AB	20-50	5.5	4.3	3.9	1.6	0.4	34.8	4.2	3.6
	Bt1	50-100	5.6	4.3	3.9	1.7	0.4	33.5	4.5	2.4
	Bt2	100-150	5.6	4.5	4.1	1.6	0.4	25.7	0.0	0.8
	Bt3	150-200+	5.7	4.8	4.5	1.2	0.3	25.0	0.0	0.5
Pedon 3	Ap	0-25	5.2	4.2	3.9	1.3	0.3	33.2	3.9	7.0
	Bt	25-75	5.6	4.6	4.1	1.5	0.5	44.1	1.7	1.3
	Bt1	75-120	5.6	4.6	4.2	1.5	0.4	26.3	0.0	0.5
	Bt2	120-200+	5.6	5.0	4.6	1.0	0.4	8.4	0.0	9.1
Pedon 4	Ap	0-30	5.5	4.5	4.0	1.5	0.5	39.4	0.2	4.4
	Bt1	30-80	5.5	4.3	4.0	1.5	0.3	12.5	2.4	2.3
	Bt2	80-125	5.5	4.4	4.0	1.5	0.4	39.4	3.8	1.0
	Bt3	125-200+	5.6	4.4	4.0	1.6	0.4	29.2	0.0	0.4
Pedon 5	Ap	0-20	6.2	5.1	4.8	1.4	0.3	47.5	0.0	7.0
	AB	20-50	5.9	5.0	4.7	1.2	0.3	45.0	0.0	4.3
	B1	50-100	5.8	4.7	4.4	1.4	0.3	43.8	0.0	3.6
	B2	100-150	5.7	5.2	4.9	0.9	0.3	42.1	0.0	1.5
	B3	150-200+	5.7	5.1	4.8	1.0	0.3	28.8	0.0	0.5
Pedon 6	A1	0-15	6.3	5.7	5.1	1.2	0.6	49.2	0.0	9.1
	A2	15-40	6.6	5.5	5.0	1.6	0.5	54.7	0.0	3.3
	B1	40-80	7.1	6.5	5.9	1.2	0.6	53.5	0.0	1.1
	B2	80-130	8.1	7.0	6.9	1.2	0.1	50.6	0.0	0.9
	BC	130-170	8.5	7.5	7.1	1.4	0.4	45.7	0.0	0.3

Table 6: Exchangeable bases, base saturation percentages and available P of study pedons

Pedon	*Horizon*	*Depth, cm*	*Exchangeable Bases (Cmolckg^{-1})*					*DS, %*	*BS*
			Ca	Mg	Na	K	*Sum*		*(%)*
PR-01	Al	0-20	0.3	3.1	0.2	0.3	3.9	67	28
	A2	20-50	0.9	0.9	0.0	0.2	1.9	72	18
	B	50-100	0.4	0.1	0.0	0.1	0.7	72	6
	Bt1	100-150	0.5	0.9	0.3	0.2	1.9	66	19
	Bt2	150-200+	0.5	0.2	0.0	0.1	0.8	76	15
PR-02	A	0-20	9.5	6.0	0.2	1.7	17.4	59	99
	AB	20-50	4.0	4.5	0.2	2.1	10.8	57	72
	Bt1	50-100	3.8	3.5	0.1	1.5	8.8	60	66
	Bt2	100-150	5.4	4.8	0.1	0.8	11.0	57	100
	Bt3	150-200+	6.2	3.9	0.1	0.6	10.8	57	100
PR-03	Ap	0-25	4.7	1.9	0.0	0.2	6.8	68	63
	Bt	25-75	9.0	1.4	0.0	0.3	10.7	72	87
	Bt1	75-120	4.7	1.5	0.1	0.3	6.5	75	100
	Bt2	120-200+	7.1	3.2	0.2	0.3	10.7	0.0	100
PR-04	Ap	0-30	6.4	3.6	0.0	1.4	11.4	71	99
	Bt1	30-80	5.8	3.9	0.0	0.9	10.6	0.0	81
	B22	80-125	4.7	3.5	0.0	0.7	9.0	68	70
	Bt3	125-200+	4.5	3.4	0.1	0.4	8.3	72	100
PR-05	Ap	0-20	18.7	4.7	0.0	0.1	23.5	51	100
	AB	20-50	14.6	5.3	0.0	0.8	20.7	54	100
	B1	50-100	14.8	3.8	0.0	0.5	19.1	57	100
	B2	100-150	9.4	4.0	0.1	0.5	14.0	67	100
	B3	150-200+	8.5	4.3	0.6	0.5	13.9	52	100
PR-06	A1	0-15	38.4	9.3	0.0	0.1	47.9	0.0	100
	A2	15-40	38.9	8.9	0.1	0.3	48.2	12	100
	B1	40-80	45.7	5.4	0.2	0.2	51.4	4	100
	B2	80-130	40.3	4.6	0.4	0.2	45.4	10	100
	BC	130-170	32.8	3.5	0.8	0.2	37.3	18	100

Table 7: Pedological processes in Didessa watershed along the study transect

Specific process	Bundles of processes	Soil properties	Pedons
Melanization	OM additions	Dark to black A horizons	1, 2, 3, 5, 6
Chelation	Translocation and precipitation	Dark red color argic horizons	1, 2, 3
Latosolization	Translocation	Mineral concretions	1, 2, 3
Fe redox	Oxidation- Reduction	Coatings and concretions	1, 2, 3, 4, 5
Colloidal eluviation	Lessivage	Clay depletion	1, 2, 3, 4, 5
Colloidal illuviation	lessivage	Clay accumulation and argic horizons	1, 2, 3, 4, 5
Leaching	De-alkalization	Basic cations, reduced Fe	4, 5
Surficial erosion		Sheet, splash and gulley erosion	4, 5, 2
Acidification	De-alkalization	pH, low basic cations, high exchange acidity	1, 2, 3, 4, 5
Calcification	Alkalization	Calcic horizon, Ca concretions, filamentous, effervescence to 10% HCl	6
Vertization	Pedoturbation	Shrink swell properties, slicken sides, cracking, gilgai	6
Ferralitization	Ferrolysis	Color, coatings, concretion	1, 2, 3, 4, 5
Braunification	Transformation	Brown color	1, 2, 3, 4, 5
Rubification	Transformation	Reddish brown color	1, 2, 3, 4, 5
Ferrugination	Transformation	Red color	2, 3, 4, 5

Table 8: Soil classifications of according Soil Taxonomy and WRB classification systems

Pedon	Soil Taxonomy	WRB
1	Typic Hapludults	Ferric Rhodic Alisols (alumic, cutanic, loamic)
2	Typic Ferrudalfs	Ferric Rhodic Luvisols (cutanic, loamic, hypereutric)
3	Typic Ferrudalfs	Ferric Chromic Luvisols (clayic, cutanic, hypereutric)
4	Typic Rhodudalfs	Ferric Rhodic Luvisols (clayic, cutanic, hypereutric)
5	Typic Rhodudalfs	Ferric Rhodic Luvisols (clayic, cutanic, hypereutric)
6	Typic Hapluderts	Calcic Pellic Vertisols (clayic, cutanic, gilgaic, hypereutric)

Table 9: Twenty years annual climatic data of some metrological stations in and around Didessa watershed

Stations	Elevation	UTM		Temperature, °C			Rain fall	PET	LGP, days
		Lat.	Long.	Min.	Max.	Mean	mm		
Arjo	1306 m	196967	999967	12	26	19	1837	1287	210
Atnago	1787 m	274209	918668	12	26	19	1759	1299	205
Sire	1815 m	265668	999900	11	26	23	1886	1305	193
Gimbi	1940 m	151881	1014417	13	26	19	1920	1273	198
Bedele	2000 m	209325	935564	12	26	19	1887	1283	198
Rob Gebeya	2001 m	271771	1013237	16	28	19	1400	1441	192
Kone	2005	201645	961679	13	26	19	1771	1287	196
Dembi	2007	220296	895352	12	26	19	1799	106	194
Nekemte	2010	230536	1005760	12	26	19	1705	1280	198
Getema	2053	223837	984039	12	26	19	1837	1287	165
Yembero	2189	220082	904183	12	26	19	1909	106	172
Meko	2229	172596	961334	13	26	19	1846	1272	198

Table 10: Location and site characteristics around studied pedons

Pedon	Location (UTM)		Topography		Slope		
	Lat.	Long.	Alt.	Position	Positions	Percent	Form
Pedon 1	37P-0222356	1007353	2050 m	Highland	Upper	5	Concave
Pedon 2	37P-0224349	0998258	2257 m	Highland	Upper	3	Concave
Pedon 3	37P-0221899	0978308	2543 m	Highland	Summit	4	Straight
Pedon 4	37P-0222888	0965884	2246 m	Highland	Middle	5	Concave
Pedon 5	37P-0219304	0964683	1622 m	Midland	Foot Slope	4	Concave
Pedon 6	37P-0216241	0959114	1273 m	Lowland	Toe Slope	2	Straight

Table 11: Vegetation types and major land uses around study pedons

Pedon	Vegetation types	Land uses	
		Types	Descriptions
Pedon 1	Woodland	*Coffee arabica* plantation	Fifteen years mature Coffee arabica plantation under shade of mature woodland trees of about 50 years of age
Pedon 2	Woodland	*Eucalyptus* plantation	Fifteen years old *Eucalyptus* plantation
Pedon 3	Woodland	Annual rain fed arable field cropping	Cultivated for over forty years under rain fed arable field cropping and highland legumes (Faba bean and field pea)-*Eragrostis tef*-barley-noug in rotation without short fallow period
Pedon 4	Woodland	Annual rain	Cultivated for over forty years of rain fed arable
		fed arable field cropping	field cropping and highland legumes (Faba bean and Field pea)-*Eragrostis tef*-barley-noug in rotation without short fallow period
Pedon 5	Wood and tall grassland	Annual rain fed arable field cropping	Cultivated for less than fifteen years of arable field cropping, not fallow cropping and less intensively cultivated
Pedon 6	Grassland	Irrigated sugar cane cultivation	Tall grassland and scattered river terrace forest intended to be under irrigated sugar cane production

Table 12: Lithology, drainage and relief characteristics around studied pedons

Pedon	Lithology		Drainage class	Land form	Micro-relief/ Erosion
	Types	Unit			
Pedon 1	Tertiary	Lower basalt	Well	Level Plateau	Sheet erosion
Pedon 2	Tertiary	Lower basalt	Well	Level Plateau	Sheet erosion
Pedon 3	Tertiary	Middle basalt	Well	Level plateau	Sheet and rill erosion
Pedon 4	Tertiary	Middle basalt	Well	Level Plateau	Sheet and rill erosion
Pedon 5	Precambrian	Granite	Well	Level Plain	Sheet and inter rill
Pedon 6	Sedimentary	Alluvium	Imperfect	Level Plain	Gilgai

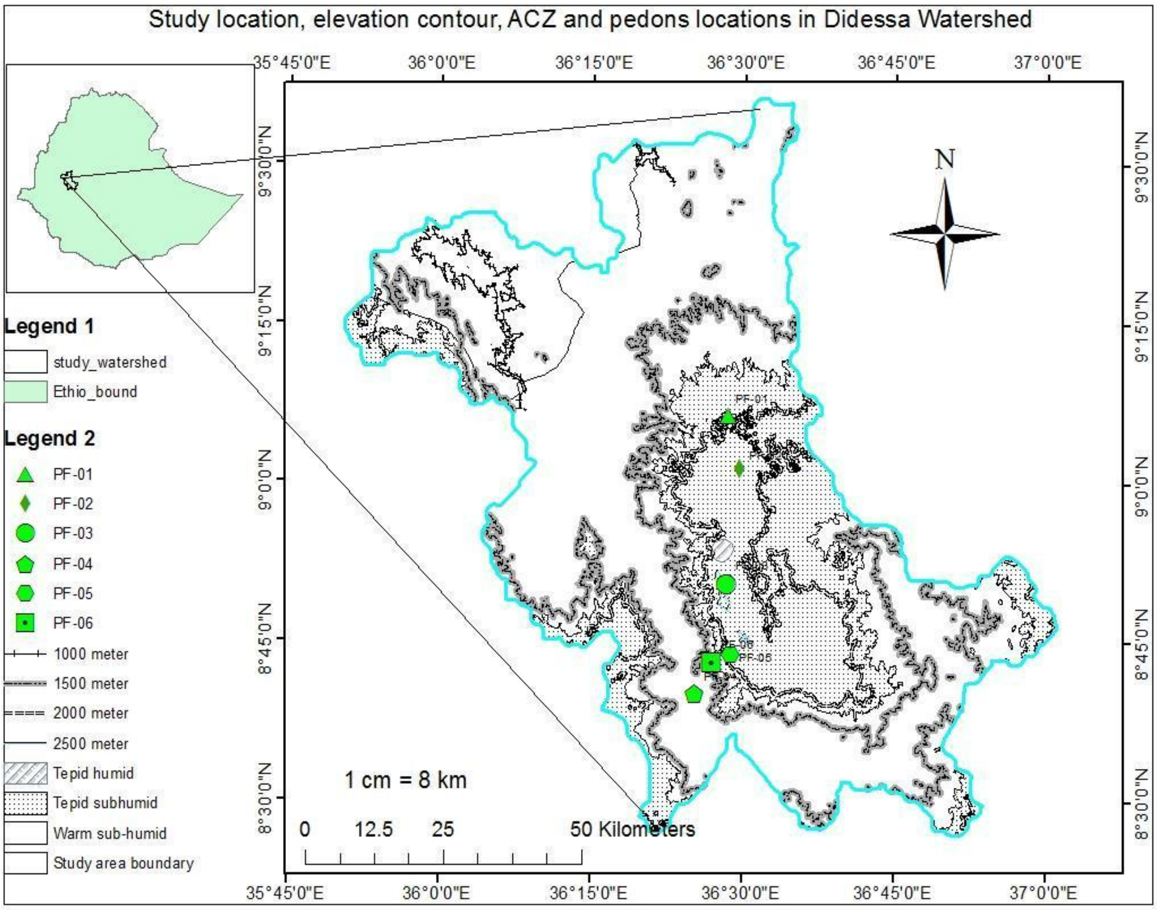
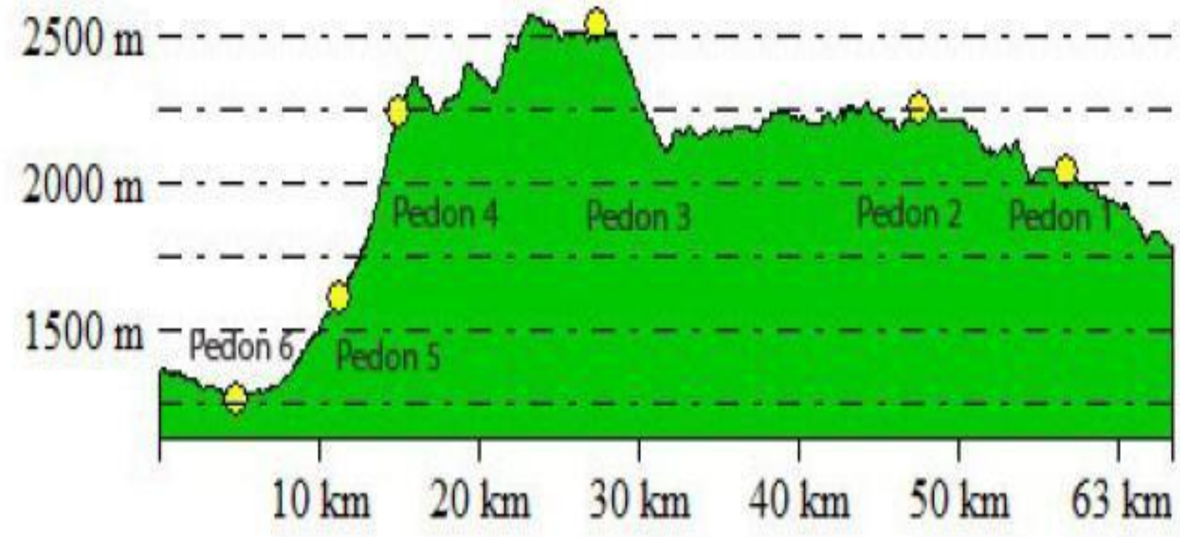
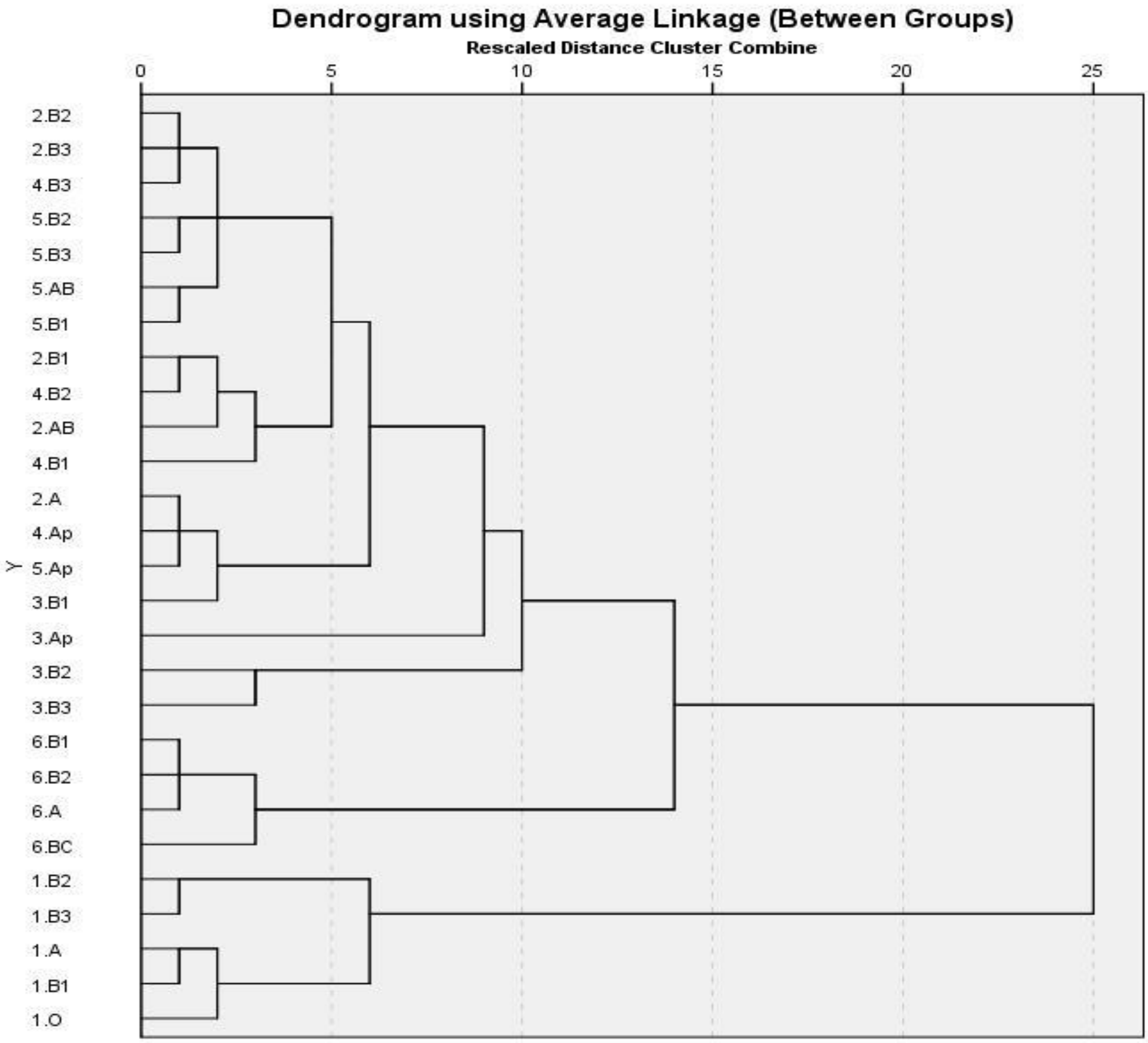


Figure 1: Didessa watershed, study transect and location of pits along elevation gradient (250 meter contour intervals)



Parameters	Pedon 6	Pedon 5	Pedon 4	Pedon 3	Pedon 2	Pedon 1
Lithology:	Alluvium	Granitic gneiss	Lower basalt	Middle basalt	Lower basalt	Lower basalt
Moisture:	Udic	Udic	Udic	Udic	Udic	Udic
LGP (days)	180-240	180-240	180-240	240-300	180-240	180-240
T °C	20-27	20-27	15-20	15-20	15-20	15-20
T °C regimes:	Hyperthermic	hyperthermic	Thermic	Thermic	Thermic	Thermic
AEZ	Warm sub humid	Warm sub humid	Tepid sub humid	Tepid sub humid	Tepid sub humid,	Tepid subhumid
Vegetation	Grassland	Grass-woody mix	Woody	Woody	Woody	Woody
Land uses:	Grassland	Cultivated	Cultivated	Cultivated	Eucalyptus plantation	Coffee forest
Soil types:	Typic Hapluderts	Typic Rhodudalfs	Typic Rhodudalfs	Typic Ferrudalfs,	Typic Ferrudalfs	Typic Hapludults
	Calcic Pellic Vertisols,	Ferric Rhodic Luvisols,	Ferric Rhodic Luvisols	Ferric Chromic Luvisols	Ferric Rhodic Luvisols	Ferric Rhodic Alisols

Figure 2: Topographic map of the study transect and locations of pedons with landform and climatic characteristics



The first numbers in vertical column indicated the profile number followed by horizons and horizons sequences

Figure 3: Relationships and classification of soil horizons in different profiles by Dendrogram using average linkages between the different horizons in the study pedons